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Beamline Errors and Corrector Strengths

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1 Introduction

Errors in the placement of magnets within a beamline can contribute to the distortion of the central trajectory. If the distortion of the central trajectory is too large, beam loss occurs reducing transmission. In addition, if the transfer line consists of a string of bending magnets powered by a single supply, the random distribution of field strength errors, for a given excitation current, may contribute to these central trajectory distortions. By evaluating the magnitude of these distortions alignment tolerances and dipole corrector strengths are estimated.

Since both the MI-52 to F0 (Tev proton injection, also called the P1 beamline) and the MI-62 to F0 (Tev pbar injection, also called the A1 beamline) beamlines are essentially identical, only the first will be investigated here. The Main Ring remnant from F0 to A0 works now (in principal) with the same BPM - corrector combination for 8 and 150 GeV, so unless all magnets are replaced in this section there is no reason to suspect it won't work in single pass operation at 8 and 120 GeV. However, all beamlines for the MI complex will eventually undergo this analysis. In addition, the results of a single correction of the worst case in the Booster to Main Injector 8 GeV (denoted as the P8 beamline) line will be presented.

2 Beamline Aperture

The transport section of the MI-52 to F0 transfer line consists of a FODO lattice of 10 half cells plus a matching section at the Tevatron end. All quads in the FODO cells (except 2) are on a single bus and all dipoles (except 1) are on a common bus. Most dipoles in this section are rolled to provide the required horizontal and vertical separation between the MI and Tevatron and satisfy the matched dispersion criteria. The dipoles are arranged in families with roll angles of 0, 4.08, 7.57, 12.02, and 23.4 degrees.

This section of beamline will be required to transport 8.9 GeV/c protons and pbars, 120 GeV/c protons for slow spill and pbar production, and 150 GeV/c protons for the Tevatron. The beamline optics remains constant for each of these scenarios with the exception of the downstream matching section which will be tuned between the 8.9 GeV/c and 150 GeV/c cycles. (The 120 GeV/c cycle has the same tune as the 8.9 GeV/c cycle.) Figure 1 shows a 40π beam envelope and magnet apertures for the 150 GeV/c Tevatron injection optics from MI-52 to Tev F17. Figure 2 shows the same envelope and apertures but for the 8.9 GeV/c pbar injection optics from MI-52 to MR F17. Note: the magnet apertures are for central orbits and do not reflect any reduction in aperture due to any rolls.

Figure 3 shows a cartoon of the aperture and lattice functions for the half cell between quads Q10 and Q11. Here these adjacent dipoles have the maximum relative difference in roll angles of 23.4 degrees. The cartoon displays the 99% beam envelope for 8 GeV beam with a normalized emittance of 40 π at three locations through the dipole pair. For comparison, the 150 GeV envelope is displayed at point 3. The available aperture in the vertical plane ranges from ± 4.25 mm at point 3 to ± 15 mm at point 1 for 8 GeV and ± 20 mm for 150 GeV. These serve to give an estimate of the magnitude of central trajectory distortions that can be tolerated for this beam line. From this cartoon, the main concern for this transfer line seems to be the avaliable aperture through the rolled dipoles for transferring 8 GeV pbars from the Source for injection into the MI.

3 Errors

The main sources of error that contribute to horizontal trajectory error include a) random errors in the dipole field ($\Delta B/B$) of the bends on a common bus and b) the horizontal misalignment of the quads (DX). The main sources of error that contribute to vertical trajectory error include c) the vertical misalignment of the quads (DY), and; d) random dipole roll errors of the (mainly) horizontal bending dipoles (DPSI). Roll errors in the vertical bends in the same way will contribute to the horizontal trajectory error. Other potential sources of alignment errors such as errors in the pitch and yaw of dipoles and quads may reduce aperture but don't create orbit distortions.

Estimates from the Alignment Group indicate that reasonable 2σ (95%) numbers for quad positioning and setting of roll angles for B2's are ± 0.50 mm and ± 1.0 mr, respectively. For this evaluation the 1σ values of ± 0.25 mm and ± 0.5 mr are used. The maximum expected kicks, based on these errors, with the nominal quad gradients and dipole fields are summarized in Table 1:

Table 1: Maximum expected errors

Error	Magnitude (2σ)	Field [kG]	Gradient [kG/m]	$\Theta[\mu r]$
quad DX,DY	0.5 mm		200	42.6
B2 dipole DPSI	1.0 mr	18.8		22.8
C-mag(V) DPSI	1.0 mr	12		7.2
B2 field $\Delta B/B$	50 units			114

The rms value of these errors in the horizontal and vertical planes are 86 μr and $28\mu r$, respectively. The 1σ value (of 25 units) for the B2 field error, derived from magnet measurements, was obtained from the 150 GeV value reported in MI note MI-0066 and is assumed to be constant for all energies. Subsequent evaluation of the dipole field measurements tends to reduce this number and, if dipoles are measured prior to installation, the $\Delta B/B$ value may be reduced even further. However, for this evaluation the measurements from MI-0066 will be used.

To estimate the effect of field errors and misalignments, these errors were introduced into the lattice and the central trajectory was calculated via the

TWISS command in MAD. Each dipole and quad in the line was assigned a random error generated from a Gaussian distribution with a 1σ value derrived from Table 2. The quad alignment and dipole roll errors are consistent with those used for Main Injector tracking at 8 GeV as found in MI-0066. Figure 4 shows the distribution of trajectories from twenty seeds based upon the errors listed in Table 2. The maximum distortion occurs at the end of the line: in the horizontal plane it is ± 14 mm, while in the vertical it is only ± 5 mm. As a test to determine how good the statistics were for 20 seeds, a run of 200 random seeds was made as shown in Figure 5. Here, the maximum distortion also occurs at the end of the line: in the horizontal plane it has increased to about ± 22 mm, while in the vertical it increased to about ± 10 mm showing an increase in maximum amplitude of approximately a factor of two. Removing the 25 units of field error, but retaining the same alignment tolerances for the 20 seed run, reduced the horizontal distortion by a factor of 2, while the vertical distortion was unaffected. This is shown in Figure 6. The alignment tolerances, σ(DX), σ(DY), σ(roll), were relaxed by a factor of four while keeping the $\sigma(\Delta B/B)$ constant as shown in Figure 7. Here the vertical distortion shows the factor of four increase while an increase in the horizontal distortion appears only in the first half of the line.

Table 2: Errors used in Central Trajectory Calculation

Error	1σ
quad misalignment (DX,DY)	0.25 mm
B2 dipole roll error (DPSI)	0.5 mr
C-mag(V) roll error (DPSI)	0.5 mr
random B2 field error ($\Delta B/B$)	25 units

4 Correctors

For this evaluation it is assumed that every quadrupole has an associated BPM and corrector. Recycled Main Ring BPM's and dipole correctors will be used in each line. Table 3 summarizes the available strength of these correctors and the maximum expected correction angle at 8.9 and 150 GeV/c, respectively. It is assumed these correctors can run 6 Amps rms for 8.9 GeV/c usage and ramped to 12 Amps for 150 GeV usage.

Table 3: Main Ring Corrector strengths

Type	Bdl/Amp [kG-m/amp]	Θ_{8GeV} [μr]	Θ_{150GeV}[μr]
Normal H	0.0345	699.3	82.8
Shimmed H	0.0259	525.0	62.1
Double H	0.0586	1178.8	140.6
Normal V	0.0202	409.5	48.5

The physical slot length for these correctors is less than 12 inches so if more strength is required multiple correctors at a single location may be run in series. Currently, there are on the order of 108 each of horizontal correctors (which would have to be shimmed) and vertical correctors in the Main Ring. Table 4 summarizes the numbers of correctors in Main Ring. Since F-sector will remain intact, the number available for use in in the beamlines is reduced. There are typically three double strength horizontal dipole correctors in each straight section of the Main Ring (except for B0) for a total of 15 and with 5 spares we have a total of 20 for use in the beamlines. The 8 GeV line would use about 26 of normal horizontal and vertical correctors with the remainder going to the 150 GeV lines. Each of the 150 GeV lines would require about 7 horizontal and 7 vertical corrector locations.

Table 4: Main Ring Corrector Inventory

Location	H Corr	Mod. H Corr	V Corr
A0 to F0	79	12	91
F0 to A0	15	3	20
Spares	15	5	4
Total	109	20	115

5 Central Trajectory Correction

Seed #1357 in the 20 seed run exhibited the maximum excursions for the each of the planes. The trajectory distortion due to this seed was selected for correction. The MATCHING function in MAD was selected to find a set of corrector strengths that would reduce the distortion to within acceptable limits. This function uses a gradient minimization technique found in MINUIT. **Note:** The closed orbit correction algorithms in MAD require a periodic solution and therefore are not applicable to beamlines without a closed periodic solution. Six different cases were investigated to ensure correction at both 8 GeV and 150 GeV. Table 5 summarizes the constraints on the central trajectory and correctors for each of the cases. Table 6 summarizes the rms and maximum corrector strengths required for correcting the central trajectory to within the specified positions. The individual errors for seed #1357 assigned to each element from the MAD output are shown in Figure 8.

Table 5: Position & corrector constraints for Central Trajectory Correction

case No.	run No.	Energy GeV	BPM's 2-14 [mm]	Inj. BPM's [mm]	$\Theta_H(max)$ [μr]	$\Theta_V(max)$ [μr]
1	1g10	8	0.0	0.0	±1000	±1000
2*	1g15	8	0.0	0.0	±1188	±409
3	2g19	150	±10	0.0	±62	±48
4	2g13	150	0.0	0.0	±140.6	±48.5
5	2g20	150	±10	0.0	±40.6	±48.5
6**	2g21	150	±10	0.0	±140.6	±48.5
7***		150	0.0	0.0	140.6	97.0

* alignment and roll errors increased by x4
* alignment and roll errors increased by x2
** orbit distortions for 19 seeds

Cases 1 and 2 constrained corrector strengths to 8 GeV levels, while the remaining cases concentrated on the 150 GeV correction. In Case 1 the maximum allowed strengths for both horizontal and vertical correctors was set to ± 1000 μr. Figure 9 shows the orbit before and after correction. The maximum corrector strengths required to correct the orbit were 99 μr and 78 μr for horizontal and vertical, respectively. This is well within the range of the shimmed horizontal corrector and normal vertical corrector listed in Table 3.

In Case 2 the 1σ values used in generating the alignment errors for quad placement and dipole roll were increased by a factor of four. Also, the maximum allowed corrector strength was set to that of a double strength horizontal corrector and normal vertical corrector. The before and after orbits for Case 2, shown in Figure 10, are also well corrected. Again, the maximum corrector strengths are well within the range of the shimmed horizontal corrector and normal vertical corrector listed in Table 3.

Case 3, the first at 150 GeV/c, constrained the maximum corrector strength to that of the 150 GeV value for the **shimmed horizontal correctors**and normal vertical correctors. Additionally, the horizontal and vertical orbit was constrained to be within ± 10 mm throughout the line and 0.0 mm through the Tev injection c-magnets and lambertsons. Figure 11 shows the results of this fit. Here, the fit is successful but it requires more than one corrector in each plane at its maximum corrector strength.

Case 4 utilized the **double strength horizontal correctors** and normal vertical correctors. The orbit was constrained to be 0.0 mm at **all** BPM's. The results are shown in Figure 12. Here, the rms horizontal value is only half the available strength from the double strength correctors. The rms vertical strength required is 70% of the maximum vertical corrector strength, with many correctors at their maximum value. This could be feasible but would require most locations to have two vertical correctors in series.

In Case 5 the tolerance on the trajectory was increased to ± 10 mm with the same corrector limits. The rms and maximum strength of the vertical correctors was reduced by about 20%. The rms horizontal corrector strength was reduced by about 35%, but the maximum horizontal corrector strength increased by about 20%. The resulting orbit before and after correction is shown in Figure 13. Here, the maximum required strengths (H and V) are still only about 85% of the maximum corrector strength at 12 Amps.

In Case 6, the alignment errors were increased by a factor of two and the corrector strengths were constrained to double strength horizontal and normal strength vertical correctors. The orbit was allowed to have a maximum of ± 10 mm ,except for the injection BPM's. Figure 14 shows that this orbit can be corrected with 50% rms horizontal strength and 80% of the vertical corrector strength. However at least one corrector in each plane is at a level greater than 90% of the maximum value.

In Case 7, the orbit distortions were corrected due to the 20 random shown in figure 4. The horizontal correctors were constrained to be **double strength horizontal correctors** at each QF location and **two normal vertical correctors** at each QD location. Figure 15 shows the corrected orbits for 19 out of the 20 seeds (one seed was prematurely ended). At least one horizontal corrector at its maximum strength was required while only 75% of the available vertical strength was used. These corrections required approximately 24 hours of cpu time on Sun Sparcstation IPC. It is clear that good statisitcs cannot be obtained in a reasonable amount of time.

Table 6: Required Corrector Strengths for Central Trajectory Correction

case	Energy	$\Theta_H(rms)[\mu r]$	$\Theta_H(max)[\mu r]$	$\Theta_V(rms)[\mu r]$	$\Theta_V(max)[\mu r]$
1	8	62	99	41	78
2*	8	113	166	150	272
3	150	49.6	62.1	37.2	47.8
4	150	68.8	98	32.9	48.5
5	150	44.7	115	26	41
6**	150	74.3	121.7	38.5	47.7
7***	150	60.6	140	28.6	65.6

* alignment and roll errors increased by x4
* alignment and roll errors increased by x2
** rms and max values for 19 seeds

6 Booster to MI 8 GeV Line

The errors listed in Table 2 were added to the main transport section in the 8 GeV line between the Booster and Main Injector in the same fashon as was done for the MI-52 to F0 line.[1] The transport cell structure consists of 14 FODO cells with all dipoles on a single bus. Twenty seeds were used to obtain a distribution of central trajectory errors, as shown in Figure 16. The maximum excursions of the trajectories are ± 42 mm and ± 12 mm for horizontal and vertical, respectively. The "worst case" distortion from the 20 seeds was corrected using the MICADO algorithm in MAD. This smoothed the orbit to within 1 mm with the maximum dipole strengths required of $386\mu r$ and $86\mu r$ for horizontal and vertical, respectively. The orbits before and after correction are shown in Figure 17. These strengths are well within the dc levels of the existing MR shimmed horizontal and normal vertical correctors

7 Conclusions

Orbit correction for the MI-52 to F0 transfer line was accomplished for a single "worst case" orbit distortion from twenty random seeds. The standard errors used were consistent with the estimated 2σ values supplied by the Alignment group. From these few test cases the following conclusions are drawn:

- The 8 GeV correction of the P1 (A1) beamline can be done with shimmed horizontal and normal vertical correctors, even when the errors are multiplied by a factor of four. So correction at this energy should not dictate the required alignment tolerances.
- The 150 GeV correction for standard errors requires double strength horizontal correctors and normal vertical for the standard alignment errors. This requires a maximum of 85% of the available corrector strength at 12 Amps.
- With "standard" alignment tolerances (i.e. Table 1) and accepting a ± 10 mm orbit distortion (except in the matching section and injection

[1] J. Johnstone, private communication.

Lambertsons), single vertical correctors and double strength horizontal correctors would be sufficient for correcting the orbit due to the magnitude of alignment errors investigated.

- Since there is physical space for double vertical correctors at each defocussing location except Q13 and since all the vertical corrections at 150 GeV/c required at least one vertical corrector to be at greater than 90% of its maximum, it would seem prudent to use two vertical correctors at each defocussing quad location.

- Orbit control for Tevatron injection of Main Injector injection has not been taken into account in this analysis except to note the potential use of existing bunp magnets in the Main Ring. These may replace or be in addition to the orbit correctors discussed here.

- Currently, the orbit correction routine in MAD, MICADO, requires closure and hence cannot be used here. Therefore, a program should be written to allow the correction of orbit distortions in beamlines which does not require closure. This should incorporate knowledge of the lattice, detector and corrector positions, and utilize the relationship between corrector strength and the resulting orbit downstream to minimize the required corrector strengths. This algorithm would be much faster than the MINUIT general minimization algorithm used in MAD so better statistics could be obtained.

- **Recomendation:** Based upon the above analysis the required installation tolerances shall be kept to the following for all beamlines: ± 0.5 mm for transverse placement and ± 1.0 mr for roll. With these tolerances the Booster to MI can use the shimmed horizontal correctors and standard vertical correctors while the P1 and A1 lines shall use double strength horizontal correctors at F quads and two single strength vertical correctors at the D quads.